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Linewidth-narrowing and intensity noise reduction of the 2nd order Stokes component of a low threshold Brillouin laser made of Ge₁₀As₂₄Se₆₈ chalcogenide fiber

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Abstract: A compact second-order Stokes Brillouin fiber laser made of microstructured chalcogenide fiber is reported for the first time. This laser required very low pump power for Stokes conversion: 6 mW for first order lasing and only 30 mW for second order lasing with nonresonant pumping. We also show linewidth-narrowing as well as intensity noise reduction for both the 1st and 2nd order Stokes component when compared to that of the pump source.

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1. Introduction

Brillouin fiber lasers (BFLs) have been attracting a lot of interest lately due to their very narrow linewidth [1] and low intensity [2] and frequency noise [3]. 1st order Stokes (S1) Brillouin ring lasers in silica fibers have been exploited for many applications ranging from microwave photonics applications [4] to gyroscopes [5]. A 2nd order Stokes (S2) component, oscillating in the opposite direction of S1, can be obtained in such BFLs if the intensity of S1 component is high enough. One can expect that the generated S2 component will have better spectral characteristics than the S1 component due to the linewidth-narrowing effect in BFLs [6].

Silica-based optical fibers are often used to make Brillouin ring cavities. A resonant pump is often used in those cavities to obtain low laser thresholds [3, 4]. However, this requires the use of a locking loop for stable operations making the setup complicated and expensive. Simpler cavities can be achieved by using a nonresonant pump. The use of a long ring cavity is required to reach reasonable laser threshold due to the relatively small Brillouin gain coefficient g_B of 4×10^{-11} m/W in silica [7], but this may lead to multi-frequency laser emission. Chalcogenide microstructured optical fibers (MOFs) are an attractive option to make compact, single-frequency BFLs since the high g_B (two orders of magnitude higher than that of a silica fiber) of these fibers [8] combined with a reduced mode effective area brought by the microstructure can guarantee low laser threshold.

In a previous work, a relatively low laser threshold of 22 mW was obtained for nonresonant pumping in a BFL made of a 3-m long suspended-core $As_{38}Se_{62}$ chalcogenide fiber [9]. This laser had also very good intensity and frequency noise characteristics. Our goal being to study the S2 component in this communication, we have replaced the suspended-core chalcogenide $As_{38}Se_{62}$ fiber previously used with a microstructured $Ge_{10}As_{24}Se_{68}$ (GeAsSe) fiber having a reduced transmission loss in order to obtain the lowest possible laser threshold for 1st and 2nd order Stokes component. The fabrication process as well as the Brillouin characterization of this fiber will be discussed in section 2.

The purpose of this communication is twofold: first to demonstrate the possibility of making compact BFLs operation on 2nd order Stokes component with a relatively low threshold power (section 3) and, second, to experimentally demonstrate the coherency and intensity noise performances of the S2 component generated in the cavity (sections 4 and 5).

2. Microstructured GeAsSe chalcogenide fiber

The GeAsSe MOF (figure 1(a)) used in this paper is prepared with high purity glass. A $Ge_{10}As_{24}Se_{68}$ glass rod is previously purified thanks to several synthesis steps using a small

amount of oxygen and hydrogen getter. Then, the preform is prepared by using a casting method [10]. The chalcogenide glass is heated around 500°C and flowed into a silica mould which contains aligned silica capillaries. This method enables the realization of low loss fibers. During the drawing step, the hole sizes are adjusted by applying a positive pressure in the preform [11]. The external diameter of the GeAsSe suspended-core fiber is 140 μm and the core diameter d is 3.8 μm . The mode effective area was estimated to be around 8 μm^2 and the fiber losses α were found to be 0.65 dB/m at 1.55 μm .

A complete experimental characterization of Brillouin scattering in our GeAsSe MOF was realized. A g_B of 4.5×10^{-9} m/W was determined using the setup and method detailed in reference [12]. A spectral characterization of the Brillouin gain spectrum was also done using a heterodyne detection from which a Brillouin frequency shift ν_B of 7.25 GHz and a Brillouin gain linewidth $\Delta\nu_B$ of 17.6 MHz were measured. The values of g_B , ν_B and $\Delta\nu_B$ are slightly different from the measured values for a suspended-core AsSe fiber [12] but can be explained by the presence of germanium in the fiber composition [13].

3. Brillouin laser made of microstructured GeAsSe chalcogenide fiber

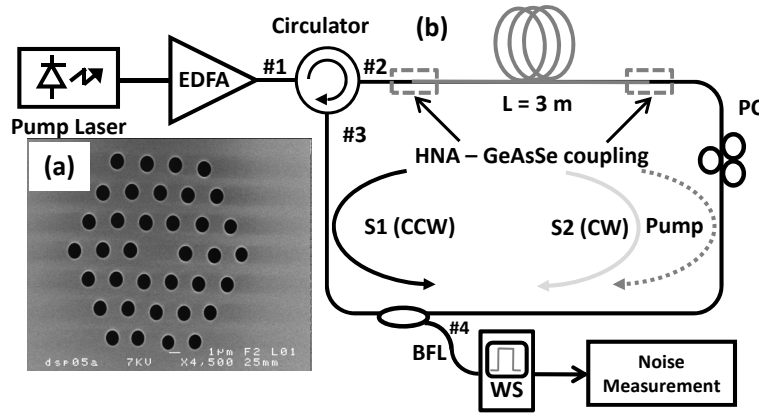


Fig. 1. (a) Transverse section of the GeAsSe MOF used and (b) experimental setup of the BFL laser cavity. Abbreviations are as follows: EDFA (Erbium Doped Fiber Amplifier); HNA (High Numerical Aperture); PC (Polarisation Controller); S1 and S2 (1st and 2nd order Brillouin lasing); CW (Clockwise); CCW (counterclockwise).

The experimental setup of the single-frequency BFL used in this communication is illustrated on figure 1(b). The laser cavity is composed of 3 m of GeAsSe fiber and 5 m of classical single-mode fiber resulting in a total optical cavity length of 15.08 m ($5 \times 1.45 + 3 \times 2.61$). This corresponds to a free spectral range (FSR) of 19.9 MHz, which is more than the measured $\Delta\nu_B$ of 17.6 MHz, ensuring that only one single longitudinal mode is oscillating inside the cavity. The output of the BFL is extracted from a 10 % fiber coupler while the remaining 90 % is fed back into the cavity. The ring cavity is closed by an optical circulator. This allows free propagation of the Stokes waves, which perform multiple roundtrips in the counterclockwise direction (CCW) with respect to figure 1(b), while the pump wave interacts only over a single loop in the clockwise direction (CW). The main advantage of this cavity over a conventional ring resonator cavity [14] is that there are no resonant conditions for the pump, and thus, no need to servo-lock it with a feedback loop. A polarization controller is inserted inside the cavity to ensure that the polarization of the pump is kept parallel to that of the Stokes waves to yield maximum Brillouin gain since our fiber is not polarization-maintained. The total round-trip

linear losses, which includes 1.95 dB due to transmission losses in the chalcogenide fiber, 1 dB due to Fresnel reflection, 2.5 dB of coupling losses and 2.5 dB across the optical components in the ring cavity, is estimated to be around 7.95 dB.

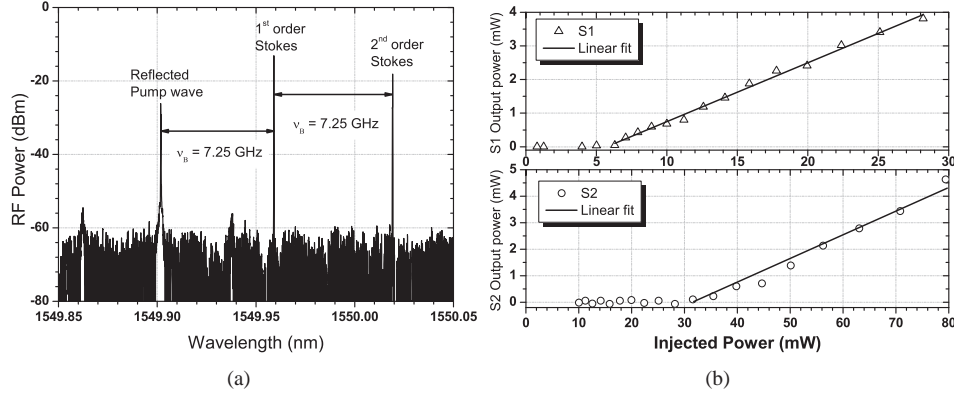


Fig. 2. (a) Brillouin laser output measured with an optical spectrum analyzer for an injected power of around 70 mW and (b) S1 and S2 output power as a function of injected pump power.

Figure 2(a) shows the optical spectrum of the BFL output measured at the output # 4 of the 90/10 coupler when around 70 mW was injected in the chalcogenide fiber. The first peak represents the Fresnel-reflected pump wave at the entry facet of the chalcogenide fiber. A second peak, downshifted by 7.25 GHz with respect to the pump frequency, was observed. It represents the 1st order Stokes which propagates in the CCW direction in the cavity. This S1 component was intense enough to generate a 2nd order Stokes component in the CW direction. The third peak thus represents part of the S2 component, Fresnel-reflected in the CCW direction (like the pump wave) and resonant in the cavity. The output power of both the S1 and S2 components were monitored for different injected power. As shown on figure 2(b), 6 mW and 30 mW of injected powers were needed for respectively 1st and 2nd order Stokes lasing in the BFL cavity.

4. Linewidth-narrowing effect in Brillouin ring cavity

A delayed self-heterodyne detection technique [15] consisting of an unbalanced Mach-Zehnder interferometer was used to investigate the linewidth of the S1 and S2 components. The output signal from the fiber laser is injected into an acousto-optic modulator (AOM) with a carrier frequency of 200 MHz generated by a RF synthesiser. The first order, shifted at 200 MHz, and the delayed zero order are combined and detected by a photodiode associated to a RF electrical amplifier. The beat RF signal is measured using an electrical spectrum analyser. A 50-km optical fiber delay line was used, which corresponds to a delay time of 240 μ s thus giving a resolution of 4 kHz to our heterodyne measurement. In order to verify the well-known linewidth-narrowing effect, which is due to the combined influence of acoustic damping and cavity feedback described in silica Brillouin ring lasers [6], the self-heterodyne spectra of the pump source, S1 and S2 components were separately measured (illustrated on figure 3(a)) and their 3-dB linewidth $\Delta\nu_{3dB}$ calculated. A semi-conductor laser with a spectral linewidth of 4 MHz was used as pump source. As expected, a narrower linewidth of 270 kHz (\approx 15 times less than the pump linewidth) was obtained for the S1 component. This S1 component, which initiated the S2 lasing process, yielded a S2 component 13.5 times finer than the S1 component

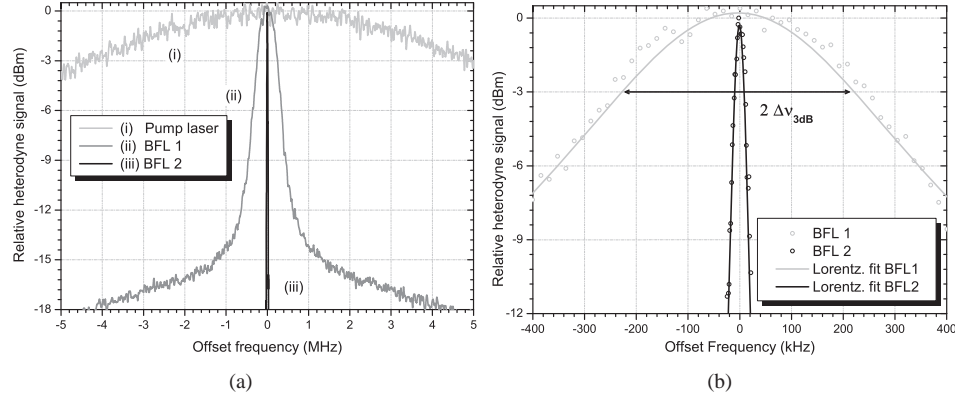


Fig. 3. (a) Linewidth measurement of the (i) pump source (ii) S1 and (iii) S2 component and (b) zoom on the central part.

(linewidth of 20 kHz). This result implies that any pump source can be made finer by exploiting its S1 or S2 component, which is obtained with only 30 mW pump power in our BFL cavity.

5. Relative intensity noise of the Stokes components

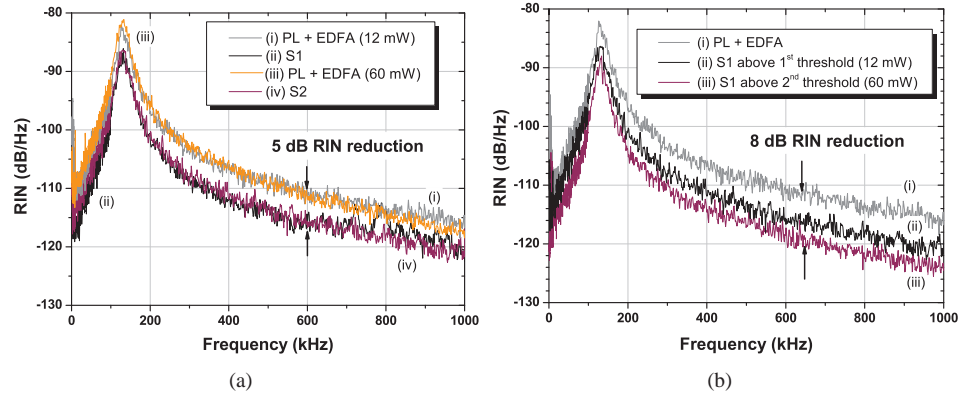


Fig. 4. RIN measurement (a) for an injected power of 12 mW for pump source and 60 mW for pump source and S2 component (b) the pump source and the S1 component operating (ii) below (12 mW) and (iii) above the second threshold (60 mW).

The Relative Intensity Noise (RIN) of the S1 and S2 components were measured using a direct detection scheme which takes into account the shot-noise of the detection system [16]. It consists in measuring the power spectral density (PSD) of the photocurrent generated by the detector by means of an electrical spectrum analyzer and normalizing the PSD by the average photocurrent. A low-noise white source was used for shot-noise calibration for the frequency bandwidth [1 kHz - 1 MHz]. The output from the BFL was filtered out using a commercial optical filter to get rid of any residual pump contribution before RIN measurement, which is plotted on figure 4(a). We have used a DFB FL (distributed feedback fiber laser) as pump source since the RIN of the semi-conductor laser used for illustrating the linewidth-narrowing effect

was too low to be measured. Note that the noise measurements are limited to 1 MHz due to the bandwidth of our low-noise transimpedance amplifier. First, 12 mW issued from the pump source (pump laser + EDFA) was injected into the GeAsSe BFL in order to generate the S1 component alone. This corresponds to a pump rate μ , defined as the ratio of pump laser power to threshold pump power, of 2. The RIN of the pump source presents a classical behaviour: a peak due to the relaxation oscillation frequency (ROF) at around 150 kHz followed by a decrease at higher frequencies as shown on figure 4(a). Beforehand one would expect the pump-to-Stokes RIN transfer function to filter out part of the pump intensity noise in the RIN measurement of the BFL as theoretically predicted in [2] and experimentally confirmed in [3, 9]. Indeed, this ROF peak is transferred to the BFL with an overall noise reduction of about 5 dB for the S1 components as compared to the RIN of the pump source (figure 4(a)). The same experiment was repeated by increasing the gain of the EDFA such that an injected power of 60 mW is obtained in order to generate the S2 component in the cavity with the same μ ($= 2$) for the S2 laser component as that used earlier. A similar RIN was obtained for the pump source. The S2 component was separated and its RIN measured as illustrated on figure 4(a). Note that the RIN of our chalcogenide BFL is similar whether it operates on 1st or 2nd order Stokes. This implies that exploiting the S2 rather than the S1 component in order to obtain a much more coherent source does not bring additional intensity noise but does not bring additional noise reduction as well.

However, the RIN of the S1 component of the chalcogenide BFL is reduced when the BFL is pumped above the second order threshold such that a S2 component is generated. When pumped between the 1st and 2nd order thresholds (12 mW) a 5 dB RIN reduction of the S1 component was obtained. Above the second threshold (60 mW), one can obtain an even higher RIN reduction (more than 5 dB) is obtained for S1 as shown on figure 4(b). This can be explained by the fact that above the second order threshold, all the intensity noise is transferred only to the S2 component such that the RIN of the 1st order Brillouin lasing is reduced.

6. Conclusion

In conclusion, a 3-meter long Brillouin fiber laser made of microstructured chalcogenide Ge-AsSe fiber and operating on the 2nd order Stokes has been demonstrated for the first time to our knowledge. This Brillouin laser required only 6 mW and 30 mW of injected power in the fiber for respectively 1st and 2nd order Stokes lasing in a nonresonant pump cavity. We hope to achieve even lower laser threshold for the 1st and 2nd order conversion by the use of fiber with reduced mode effective area and reduced transmission losses thus paving the way for BFLs with a threshold power of the order of the milliwatt for single-pass pumping. The linewidth-narrowing effect as well as the intensity noise reduction were also experimentally demonstrated for the different Stokes component generated from our laser cavity. The GeAsSe BFL can be used to increase the coherency of a random laser source by using it as pump laser. Sub-kilohertz spectral linewidth can hopefully be achieved by using an already coherent pump laser source.

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